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Optimization of venous return tubing diameter for cardiopulmonary bypass

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Abstract

Objective: To determine the optimal venous tubing diameter for adult cardiopulmonary bypass (CPB) to improve gravity drainage and to reduce priming volume. **Methods**: (A) Maximum bovine blood flow rates by gravity drainage were assessed in vitro for four different tubing diameters (1/2, 3/8, 5/16,1/4 inch) with three different lengths and various pre- and afterloads. Based on the results of (A) and multiple regression analyses, we developed equations to predict tubing sizes as a function of target flows. (C) The equations obtained in (B) were validated by ex vivo bovine experiments. (D) The clinically required maximal flows were determined retrospectively by reviewing 119 perfusion records at Zurich University. (E) Based on our model (B), the clinical patient and hardware requirements, the optimal venous tubing diameter was calculated. (F) The optimized venous tubing was evaluated in a prospective clinical trial involving 312 patients in Hangzhou. **Results**: For a mean body surface area of 1.83 ± 0.2 m^2, the maximal perfusion flow rate (D) achieved with 1/2-inch (= 1.27 cm^2) venous tubing was 4.62 ± 0.57 l/min (range: 2.50–6.24 l/min). Our validated model (B,C) predicted 1.0 cm^2 as optimal cross-sectional area for the venous line. New tubing packs developed accordingly were used routinely thereafter. The maximal flow rate was 4.93 ± 0.58 l/min (range: 3.9–7.0) in patients with a mean body surface area of 1.62 ± 0.21 m^2. **Conclusion**: The new venous tubing with 1.0-cm^2 cross-sectional area improves the drainage in the vast majority of adult patients undergoing CPB and reduces the priming volume (-27 ml/m). Reduced hemodilution can prevent homologous transfusions if a predefined transfusion trigger level is not reached.

Keywords: Cardiopulmonary bypass; Gravity drainage; Venous line; Priming volume; Extracorporeal circulation

1. Introduction

The configuration of the tubing sets for cardiopulmonary bypass (CPB) has stayed the same for many years. As early as 1962, Galletti and Brecher [1] recommended large-bore, 1/2-inch tubing for venous return. To the best of our knowledge, no systematic study has been reported since on the optimization of venous tubing diameters for CPB. Nowadays, the venous lines in standard tubing sets used in daily clinical practice for adult CPB are still based on 1/2-inch tubing although they may not be ideal. In contrast, vacuum-assisted and pump-driven venous return based on 3/8-inch venous tubing [2] provides adequate flow rate. As a matter of fact, larger tubing not only requires more material for production but also needs more priming volume and therefore results in unnecessary hemodilution. The objective of this study is to determine the optimal venous tubing diameter for adult cardiopulmonary bypass in order to improve gravity drainage and to reduce priming volume. However, as blood has to be considered a non-Newtonian fluid (its viscosity is not constant but a function of flow-dependant shear rates) in vitro, ex vivo and clinical evaluation are necessary.

2. Material and methods

2.1. In vitro flow evaluation of various tubing diameters with bovine blood

In order to determine the maximum flow rates of commercially available tubing we studied various scenarios under standardized conditions. For this purpose, we used the

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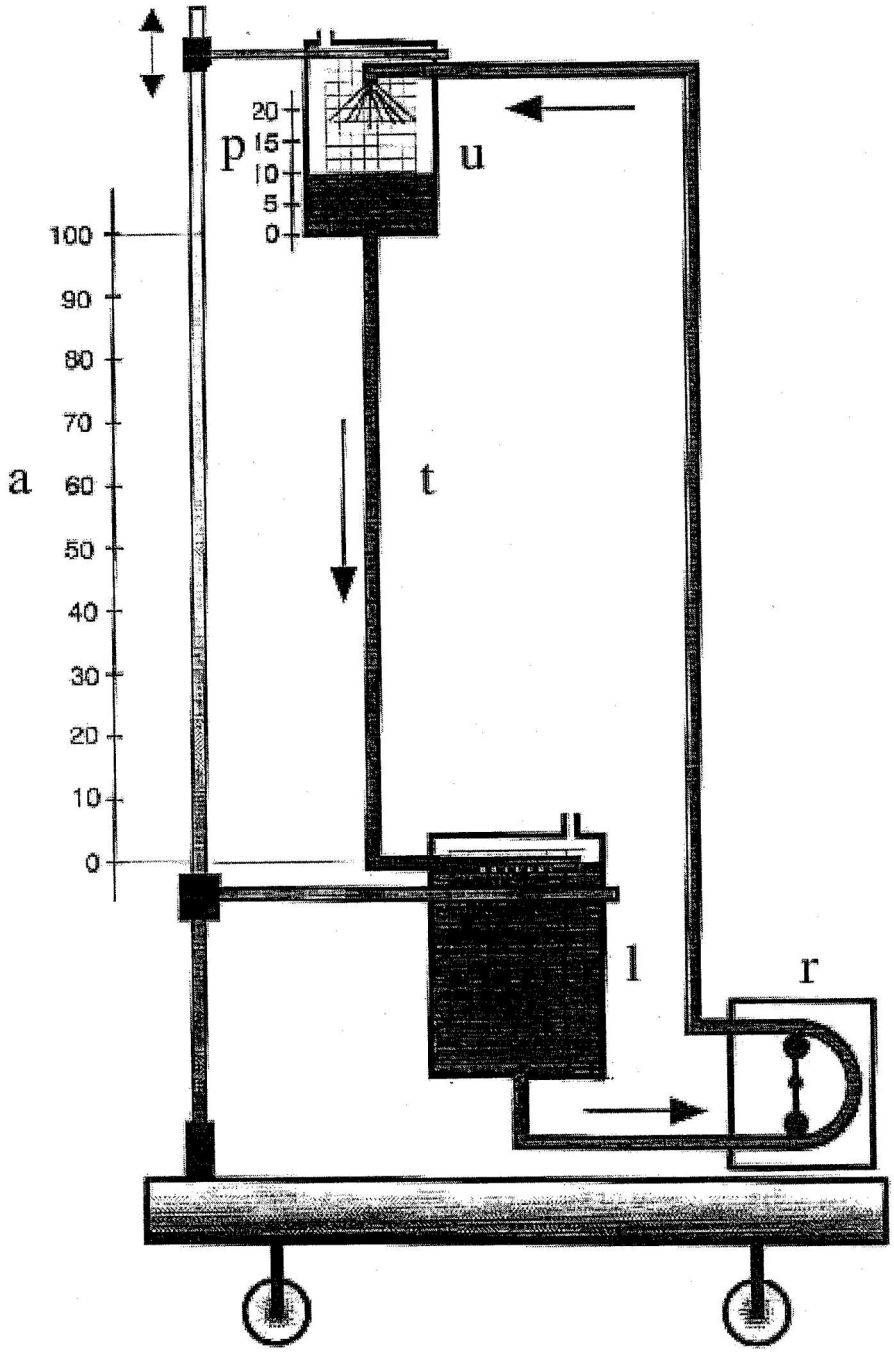

Fig. 1. Schematic view of the test set-up: upper hard shell reservoir (u), lower hard shell reservoir (l), test tubing (t), preload (p: cmH_2O), afterload (a: cmH_2O), drainage load (d = preload + afterload: cmH_2O), roller pump (r).

experimental set up shown in Fig. 1. An upper hard shell reservoir (u) is connected to a lower hard shell reservoir (l) by the test tubing (t). The vertical distance between the upper reservoir outlet and the blood level within this same reservoir is termed preload (p: cmH_2O) whereas the vertical distance between the two ends of the test tubing is termed afterload (a: cmH_2O). The vertical distance between the upper blood level and the lower end of the test tubing is termed drainage load (d = preload + afterload: cmH_2O). By the means of a roller pump (Stöckert, Munich, Germany), the blood collected in the lower reservoir was continuously pumped through an in-line flow meter back into the upper reservoir. For this study, the system was primed with heparinized fresh blood that was diluted with 0.9% saline until a hematocrit of 35% was reached. The roller pump was calibrated by a volumetric tank and timer. The maximum flow rates obtained by gravity drainage were assessed under steady-state conditions for four different tubing diameters (Dideco, Mirandola, Italy: 1/2 inch = 1.27 cm^2, 3/8 inch = 0.71 cm^2, 5/16 inch = 0.49 cm^2,and 1/4 inch = 0.32 cm^2)

with seven different lengths (1.0–2.5 m) and four different drainage loads (50–80 cmH_2O) typical for clinical application.

2.2. Development of flow-predicting equations

To evaluate the relationship between blood flow rate and the other three variables (tubing cross-sectional area, drainage load, and tubing length), multiple linear regression (Statistica, Statsoft Inc., Tulsa, OK, USA and GraphPad Prism Software Inc., San Diego CA, USA) analysis was performed. The equations established were used to predict the minimal cross-sectional areas of venous tubing required in order to achieve a target flow for given, clinically relevant, tubing lengths and drainage loads.

2.3. Ex vivo validation of optimized venous tubing

2.3.1. Animals

Ex vivo validation of the predicted minimal tubing diameters was performed in bovine experiments (body-weight: 66 ± 1 kg) after approval of the protocol by the authorizing government body. General anesthesia was started with thiopental sodium. Following endotracheal intubation, volume controlled ventilation with positive end-expiratory pressure of 5 cmH_2O was provided. Anesthesia was maintained with halothane and nitrous oxide. At the end of the procedure, the animals were killed electively.

2.3.2. Instrumentation and surgery

Standard adult PVC (polyvinyl chloride) xh [3] tubing sets (Dideco, Mirandola, Italy) and a hollow-fiber membrane oxygenator (Dideco) were used [4]. After typical instrumentation (ECG, central venous pressure line, arterial pressure line), a right thoracotomy was performed. Following systemic heparination (heparin 300 IU/kg body weight; Liquemin Roche, Basel, Switzerland), the ascending aorta was cannulated with a 24-F arterial cannula (RMI ACP.024.B, Research Medical Inc., Midvale, UT, USA). Cavoatrial cannulation was performed by inserting a 51-F two-stage cavoatrial catheter (RMI 3651, Research Medical) through the right atrial appendage with the distal marker at the level of the purse-string suture.

2.3.3. Perfusion

Oxygenator and tubing set were primed with 1700 ml of crystalloids. After initiation of cardiopulmonary bypass, mean hematocrit was $26 \pm 4\%$ and perfusion temperature was set at 32°C. Throughout the procedure the activated coagulation time (ACT, Hemochron, International Technidyne, USA) was maintained above 480 s.

2.3.4. Measurements

Two different tubings (1/2 inch = 1.27 cm^2, 3/8 inch = 0.71 cm^2) with three different lengths and two different drainage loads (central venous pressure + vertical distance between right atrium and blood level in the venous reservoir of the integrated oxygenator/heat exchanger structure: 50 and 80 cmH_2O) were analyzed. For a given scenario, the maximal pump flow achievable was read, after calibration with a volumetric tank and timer, under steady-state conditions when the level in the venous reservoir had stabilized for 2 consecutive minutes. Pump flow, central venous pressure, arterial pressure, and ECG were recorded continuously on a 16-channel computerized recording system (Hellige, Freiburg, Germany).

2.4. Review of perfusion records

In order to determine the clinically relevant maximal flow rates during routine cardiopulmonary bypass for open-heart surgery, we reviewed retrospectively 138 consecutive cardiopulmonary bypass charts at the Department of Cardiovascular Surgery of Zurich University Hospital (February 9–April 8, 1996). Nineteen cases belonged to the pediatric age group and 119 were adults (over 16 years old = study group D). The target pump flow (perfusion index) for the study group D was set at 2.50 l/min per m^2 body surface area. Standard adult cardiopulmonary bypass sets for adults were provided by Dideco. The tubing diameter for venous lines was $1/2 \times 3/32$ inch. At that time, the total length of the venous line in a standard tubing pack was 2.41 m and the material was PVC xh. The Compactflo D703 (Dideco) was the most frequently used oxygenator [3] and S3 (Stöckert) were the preferred roller pump consoles.

2.5. Theoretical calculation of optimal cross-sectional area for venous lines in routine CPB

Based on the institutional patient profile (Section 2.4), the observed maximal flows, the perfusion hardware requirements, and the validated (Section 2.3) flow-predicting equations (Section 2.2), we calculated the optimal cross-sectional area of the venous lines for routine CPB.

2.6. Development of new tubing sets and clinical evaluation

The optimized venous tubing was evaluated in a prospective clinical trial at the First Affiliated Hospital of the Medical College of Zhejiang University in Hangzhou, China. For this purpose, the usual adult tubing sets (Kun Ting, Ningbo, China) were modified with custom made venous lines designed in accordance with the specifications defined above (Section 2.5). Between February 1997 and June 1999, 312 consecutive, non-pediatric patients were included in the study. The ascending aorta was cannulated with the usual Sarns 22–24-F arterial cannulas and two-stage venous drainage catheters, or two caval catheters connected with a Y-connector were used respectively (DLP Medtronic, Grand Rapids, MI, USA). A Sarns 7400 roller pump console (Sarns Inc., Ann Arbor, MI, USA) and crystalloid/plasma priming were standard.

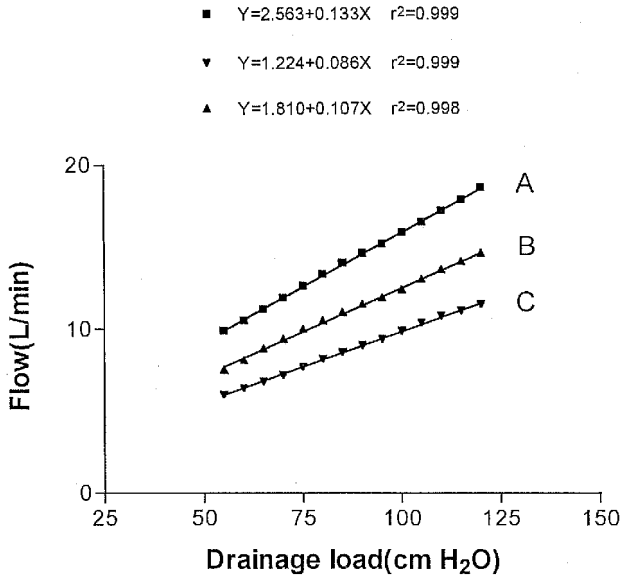

Fig. 2. Blood flow as a function of drainage load for various tubing lengths with a given diameter: 1/2 inch; A = 1 m, B = 2 m, C = 3 m.

3. Results

3.1. In vitro flow evaluation of various tubing diameters with bovine blood

The relationship between drainage load and blood flow based on linear regression analysis is depicted in Figs. 2 and 3. In order to predict the flow rate of a given tubing diameter, the relationship between cross-sectional area of the tubing and the blood flow rate for a drainage load of 60 cmH_2O is shown in Fig. 4.

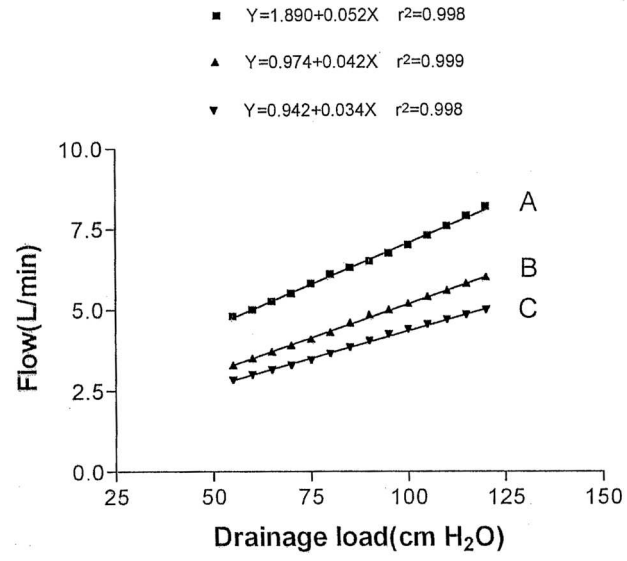

Fig. 3. Blood flow as a function of drainage load for various tubing lengths with a given diameter: 3/8 inch; A = 1 m, B = 2 m, C = 3 m.

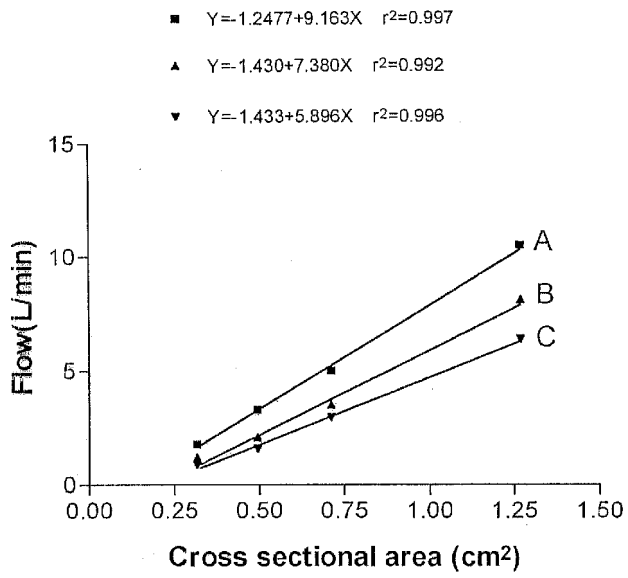

Fig. 4. Blood flow as a function of cross-sectional area of the tubing and various tubing lengths for a given drainage load (60 cmH_2O). Tubing length: A = 1 m, B = 2 m, C = 3 m. Cross-sectional area: 1/2 inch = 1.27 cm^2, 3/8 inch = 0.71 cm^2, 5/16 inch = 0.49 cm^2, 1/4 inch = 0.32 cm^2.

3.2. Development of flow-predicting equations

Based on the results of multiple regression analysis, the following predictive equations were derived that allow for determination of the optimal tubing size to achieve a certain target flow:

$$F = -2.6093 + 0.0512D - 1.2231L + 8.5016C \quad (1)$$

for F = flow, D = drainage load, L = length of tubing, C = cross-sectional area of tubing; $r^2 = 0.956$, $P < 0.0001$. Eq. (1) describes the relationship between the blood flow F and the other three variables which are the drainage load D (55–80 cmH_2O), the length of the tubing L (1.0–3.0 m), and the cross-sectional area of the tubing C (0.32–1.27 cm^2).

$$F = 6.0422 + 0.1156D - 2.3100L \quad (2)$$

for F = flow, D = drainage load, L = length of 1/2-inch tubing; $r^2 = 0.990$, $P < 0.0001$. Eq. (2) was derived to provide more precise predictive values for the blood flow as a function of drainage load and the length of 1/2-inch PVC xh tubing that is the current standard for venous lines.

$$F = 3.59544 + 0.0416D - 1.1300L \quad (3)$$

for F = flow, D = drainage load, L = length of 3/8-inch tubing; $r^2 = 0.930$, $P < 0.0001$. Eq. (3) was derived to provide more precise predictive values for the blood flow as a function of drainage load and the length of 3/8-inch PVC xh tubing that is the next smaller standard tubing diameter.

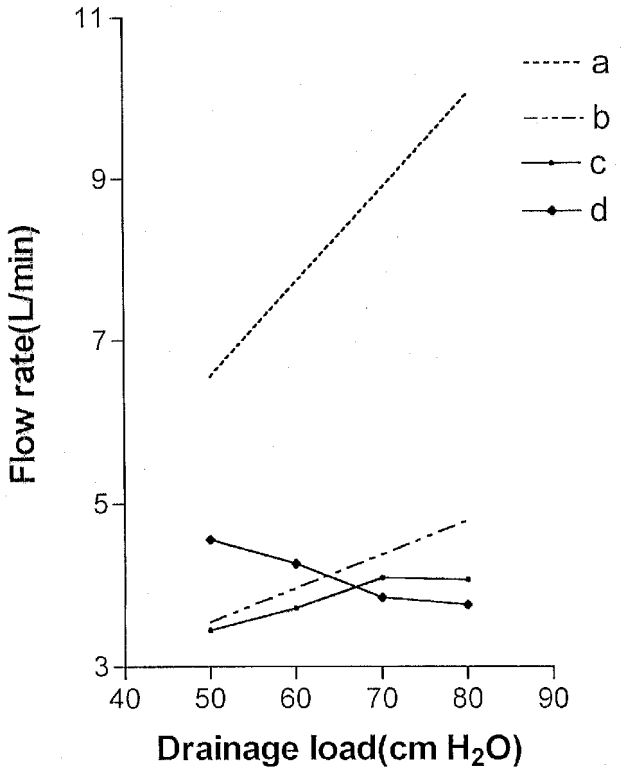

Fig. 5. Maximal flow obtained ex vivo for 1/2- and 3/8-inch tubing. For purpose of comparison the theoretical flow capacity obtained in vitro for identical tubing is plotted. a = theoretical flow rate of 1/2-inch PVC xh tubing; b = theoretical flow rate of 3/8-inch PVC xh tubing; c = observed flow rate of 3/8-inch OVC xh tubing; d = observed flow rate of 1/2-inch PVC xh tubing.

3.3. Ex vivo validation of optimized venous tubings

Eqs. (2) and (3) were derived from the experiments in vitro for prediction of the drainage performance of 1/2-inch and 3/8-inch venous lines. Fig. 5 shows the maximal flow rates obtained ex vivo with a 1/2 × 3/32-inch and a 3/8 × 3/32 PVC xh tubing measuring 2.28 m length with 50, 60, 70, and 80 cmH_2O drainage load. Ex vivo, 1/2-inch tubing provides the highest flow at 50 cmH_2O drainage load. As the drainage load increases, the flow decreases. For 3/8-inch tubing the maximum flow achieved ex vivo is at 70 cmH_2O. Higher and lower drainage load, both reduce venous return (flow). The theoretical flow curves for 1/2- and 3/8-inch tubings which were derived from the in vitro studies mentioned above are also depicted in Fig. 5. The flow-predicting line derived from the in vitro study for 3/8-inch tubing follows quite close the curve based on the ex vivo evaluation until the latter reaches its maximum. Once the top flow has been achieved, further increase in drainage load results in decreased venous return flow. In contrast, the theoretically achievable flow for the 1/2-inch tubing derived from the in vitro evaluation is never reached ex vivo. There are obviously other factors limiting the venous return with 1/2-inch tubing.

3.4. Review of perfusion records

For the 119 reviewed adult clinical perfusion protocols the mean body surface area of the patients operated on with CPB accounted for 1.83 ± 0.20 m^2. The maximal perfusion flow rate documented at any time of the procedures was 4.62 ± 0.57 l/min (range: 2.5–6.2 l/min)and the maximum perfusion flow rate per square meter of body surface area (perfusion index) was 2.54 ± 0.21 l/min. The distribution of the 119 adult patients according to their maximal perfusion flow is shown in Fig. 6. More than half of the patients (61/119) had less than 4.74 l/min and 5.24 l/min was adequate for 106/119 patients or 89%.

3.5. Theoretical calculation of optimal cross-sectional area for venous lines in routine CPB

Based on the institutional patient profile (Section 2.4), we know that 6.0 l/min CPB flow is adequate for the vast majority of central European patients. If we use a 2.0-m long venous line, 60 cmH_2O of drainage load, and wish a maximal flow rate of 6.0 l/min, our Eq. (1) as well as the solved function in Fig. 4 (cross-sectional area = (target flow + 1.43): 7.38) predict a required cross-sectional area of the tubing of approximately 1 cm^2 ((6.0 ± 1.43): 7.38 = 1.00). The theoretical blood flow with such a 1.0-cm^2 tubing for venous drainage can be calculated with Eq. (1) and are presented in Table 1.

3.6. Development of new tubing sets and clinical evaluation

The optimized venous tubing with 1.0-cm^2 cross-sectional area was evaluated in a prospective clinical trial. For the modified perfusion set the total length of the venous

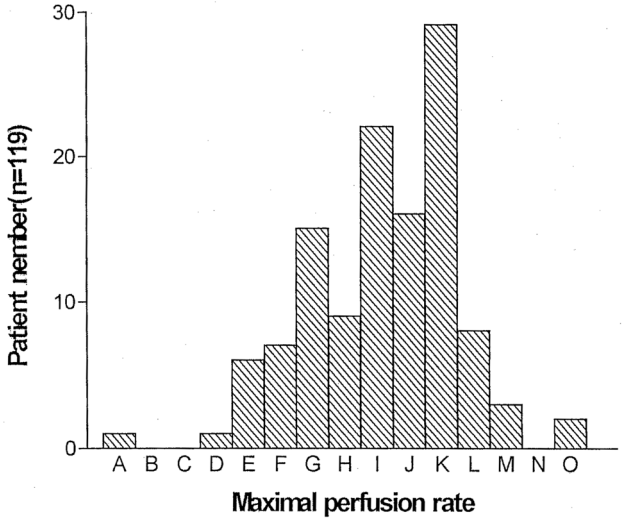

Fig. 6. Distribution of maximal perfusion flows documented during cardiopulmonary bypass for 119 adult patients. A = 2.50–2.74, B = 2.74–2.99, C = 3.0–3.24, D = 3.25–3.49, E = 3.50–3.74, F = 3.75–3.99, G = 4.00–4.24, H = 2.25–4.49, I = 4.50–4.74, J = 4.75–4.99, K = 5.00–5.24, L = 5.25–5.49, M = 5.50–5.74, N = 5.75–5.99, O = 6.00–6.24.

Table 1
Theoretical blood flow of tubing with 1.0-cm^2 cross-sectional area

Tubing length (m)	Drainage load (cmH_2O)			
	50	60	70	80
1.00	7.2	7.7	8.2	8.7
1.25	6.9	7.4	7.9	8.4
1.50	6.6	7.1	7.6	8.1
1.75	6.3	6.8	7.3	7.8
2.00	6.0	6.5	7.0	7.5
2.25	5.7	6.2	6.7	7.2
2.50	5.4	5.9	6.4	6.9

line was 2.0 m (1.8 m PVC tubing [4] and 0.2 m venous drainage catheter). For all the 312 consecutive, non-pediatric patients (age 41 ± 14 years; 164 men, 148 women) included in the study with a mean body surface area of 1.62 ± 0.21 m^2, venous drainage was adequate. The following procedures were performed: valve replacement in 256 cases, repair of atrial or ventricular septal defects in 26 cases, coronary artery bypass grafts in 11 cases, Bentall procedure in ten cases, and others in nine cases. In all patients temperature was allowed to drift, usually to 30–34°C. Mean hematocrit during perfusion was 20.9 ± 4.2% (range 15–37%). Mean perfusion time was 79.8 ± 34.7 min (range 18–319 min). The maximal cardiopulmonary bypass flow per patient was 3.9 to 7.0 l/min (mean 4.90 ± 0.58). Six patients (1.9%) died in the postoperative period, four due to either septicemia, renal failure, respiratory failure, or ventricular arrhythmia. Two patients died because of low cardiac output. Complications in survivors included respiratory complications (13 patients, 4.2%), bleeding requiring surgical revision (11 patients, 3.5%), transient neurological symptomatology (four patients, 1.3%), wound infection (four patients, 1.3%), and others (six patients, 2%). There was no evidence that any of these complications was related to the tubing used for venous drainage. No 1/2-inch tubing has been used anymore for venous drainage since this study, as the modified tubing proved to be adequate even for the weightiest patient (92 kg). The latter findings have been confirmed since in Lausanne.

4. Discussion

Optimized venous drainage lines with minimized cross-sectional area for specific perfusion requirements not only reduce priming volume but also result in improved venous drainage overall. The most obvious advantage of the new venous tubing with 1.0 cm^2 cross-sectional area as compared to the 1.27 cm^2 of the 1/2-inch tubing which is standard nowadays is the reduction of the priming volume. In fact, the priming volume of the 1.0-cm^2 tubing is 27 ml less per meter of tubing. Hence for a standard venous line of 2.0 m length, the priming volume can be reduced by 54 ml. This reduction of the priming volume has to be put in perspective with the priming volume of the other components of the cardiopulmonary bypass circuit. Today there are integrated oxygenator/heat exchanger structures available with e.g. 220 ml of priming volume. For a cardiopulmonary bypass set with such an oxygenator, the 2.0-m 1/2-inch venous line is the single most priming requiring component (254 ml). With the new 1.0-cm^2 cross-sectional area tubing for venous drainage, the priming volume of the venous line (200 ml for 2.0 m) can be kept below the one necessary for modern oxygenator/heat exchanger structures despite relying on gravity drainage. Based on the redesigned 1-cm^2 venous line, a standard complete tubing set with 1500 ml priming volume (2.0-m lines) can be reduced by 54 ml (27 ml/m) and brought to 1446 ml with otherwise identical configuration. For a 70-kg patient such new venous tubing would result in a hematocrit gain of approximately 0.2 points after full hemodilution. This may seem a minor difference. However, in clinical practice, transfusions of homologous red cell concentrates are often prescribed when predefined trigger levels are reached. Under such circumstances, it is of prime importance for the patient if the transfusion trigger level is reached or not. As a matter of fact, as little as 0.1 point hematocrit difference, which is close to the transfusion trigger level, can result in transfusion of homologous red cell concentrates with all its potential drawbacks.

However, the advantages of an optimized, smaller, venous line are not limited to the reduction in priming volume, which may attenuate the hyperdynamic response after CPB [5], and in parallel the reduction of raw material requirements for production. The main advantage of optimized venous line configurations is the improved venous drainage. Good venous drainage defined as maximal venous return for a given arterial perfusion flow is one of the main purposes of clinical cardiopulmonary bypass. Good venous return is necessary for optimal unloading of the right side of the heart and thus it is of prime importance to achieving a ‘dry’ operative field. Hydrostatic drainage [1], vacuum assist [6] or pump-driven venous return [2,7] can be used to reach this goal. For maximized hydrostatic drainage, large bore cannulas and big venous tubing, i.e. 1/2 inch, have been recommended for many years [1,8] and have been standard since for adult CPB. However, maximized negative pressure in the venous line is not equivalent to maximal venous return as demonstrated in Fig. 5, where the maximum measured flow rates for a given drainage load in vitro cannot be matched for higher drainage loads ex vivo. There are a number of reasons to explain the differences in vitro as compared to ex vivo measurements including the difficulties to realize standardized test conditions in the biological setting. However, it is well known to surgeons and perfusionists that excessive negative pressures in the venous line result in aspiration of the soft right atrial and caval tissues and consecutive occlusion of the drainage holes of the venous cannula. As a result, the blood flow

directed towards the venous cannula inlet is interrupted and some degree of blood accumulation proximal to the venous cannula is necessary to overcome the resistance of the aspirated and occasionally entrapped soft tissue. Hence, the venous return becomes to some degree pulsatile. In the operative field, this phenomenon translates into atrial 'chatter' or 'flutter' which not only intermittently fills the right-sided cavities of the heart but also translates into regular movements of the fully arrested heart and all CPB components directly connected to the venous cannula. The negative effects of excessive negative pressure are not limited to these macroscopically visible effects but can also induce hemolysis and further drawbacks at cellular and humeral levels [9] as demonstrated also for excessive suction during mediastinal shed blood recovery [10,11]. An experienced perfusionist can prevent atrial 'chatter' by electively reducing the venous return with a partially occluding clamp. Interestingly enough, continuously flowing venous return obtained either by a partial occlusion clamp on the venous line [12] or an optimized, reduced cross-sectional area of he venous line is paradoxically superior than the one that can be achieved with a fully open, oversized 1/2-inch tubing, as demonstrated in Fig. 5.

We conclude from the data presented here that optimized cross-sectional area of the venous line improves cardiopulmonary bypass. For patients requiring between 4.0 and 6.0 l/min of target CPB flow, flow required for the vast majority of adult open-heart cases, 1.0 cm^2 of cross-sectional area for 2.0 m venous line is perfectly suitable. For lower pump flows, the tubing diameters of the perfusion set should be adapted accordingly.

There can be little doubt that further improvements can be achieved by redesigning the other components of the currently used cardiopulmonary bypass sets which in general have their origins more than 50 years ago.

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